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# INJECTION OF HIGH-ENERGY ELECTRONS INTO THE INNER REGIONS OF THE MAGNETOSPHERE DURING THE MAGNETIC STORM OF OCTOBER 29-NOVEMBER 4, 1968

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ABSTRACT. Electron fluxes were measured on "Molniya-1" during a magnetic storm. The causes of the advance of the injected electron front are not reliably established.

1. Below we give the results of measuring the electron fluxes ( $E, > 250$ , /2270\*  
500 and 800 keV), carried out on the satellite "Molniya-1" (apogee 39,600 km  
in the northern hemisphere, perigee 520 km in the southern hemisphere,  
orbital inclination  $65^\circ$ , rotation period  $\sim 12$  hours) during the magnetic  
storm of October 29 - November 4, 1968.

A photomultiplier (PM) was used as the electron detector with a CsI(Tl) crystal (HC detector). Registration of the particles was done along several channels with different electric thresholds which were set according to the energy release in the CsI(Tl) crystal. The HC detector registered particles in the range of the solid angle  $24^\circ$ . The table gives the characteristics of the channels of the HC detector used in this work (parameters  $HC_1$ ,  $HC_2$ ,  $HC_3$ ).

CHARACTERISTICS OF CHANNELS OF HC DETECTOR

Scintillation HC detector	Geometric factor	Param- eter	Threshold $E_e$ , keV	Threshold $E_p$ , MeV
CsI(Tl) 3x3 mm	$10^2 \text{ cm}^2 \cdot \text{ster}$	$HC_1$ $HC_2$ $HC_3$	250 500 800	4,1 4,2 4,3

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\*Numbers in the margin indicate pagination in the original foreign text.

In addition to the electrons, protons with  $E_p \gtrsim 4.2$  MeV made a contribution to the registration of the HC detector. In the region  $L > 3.5$  all the channels register the electron component; when  $L < 3.5$  under unperturbed conditions the readings of the various channels are similar, and we may speak with confidence about the registration of electrons only in the presence of large intensity variations, when — because of the additional contribution from the electrons — the readings of the channels with various thresholds begin to differ strongly.

The relatively small (but clearly outside the framework of diffusion theory [1]) cases of electron injection into the outer radiation belt (for  $L \sim 4$ ) during moderate magnetic storms have been described in [2]. At the inner edge of the belt, diffusion waves of electrons were observed with energies in the hundreds of keV, propagating approximately 20 times more rapidly than ordinary diffusion waves observed in the region  $3.5 \leq L \leq 4$ . References [3-5] give cases of injection of electrons of various energies in the gap between the radiation belts and in the inner belt during four exceptionally strong geomagnetic disturbances. During these storms, the intensity of electrons with  $E_e \sim 300$  keV increased in the gap by more than two orders of magnitude. An important feature of these phenomena was the truncation of the injection spectra at high energies: when  $E_e > 700$  keV the variations in intensity in clouds with  $L < 3$  were insignificant.

As a result of the poor time resolution (the interval between the successive measurements comprised several days) the question as to the dynamics of injection remained open. In a number of cases, the appearance of electrons was observed in the gap, with a subsequent monotonic decay in intensity. Sometimes (for example, after the storm of May 25, 1967) along with the decay a fast diffusion advance of the front was observed from  $L \sim 2.5$  to  $L < 2$ . The distinguishing characteristic of such diffusion cases in the inner radiation belt is the high magnetic activity after the storm.

Large variations in electron fluxes for  $L < 3$  were repeatedly observed during the previous maximum of solar activity. However, these measurements

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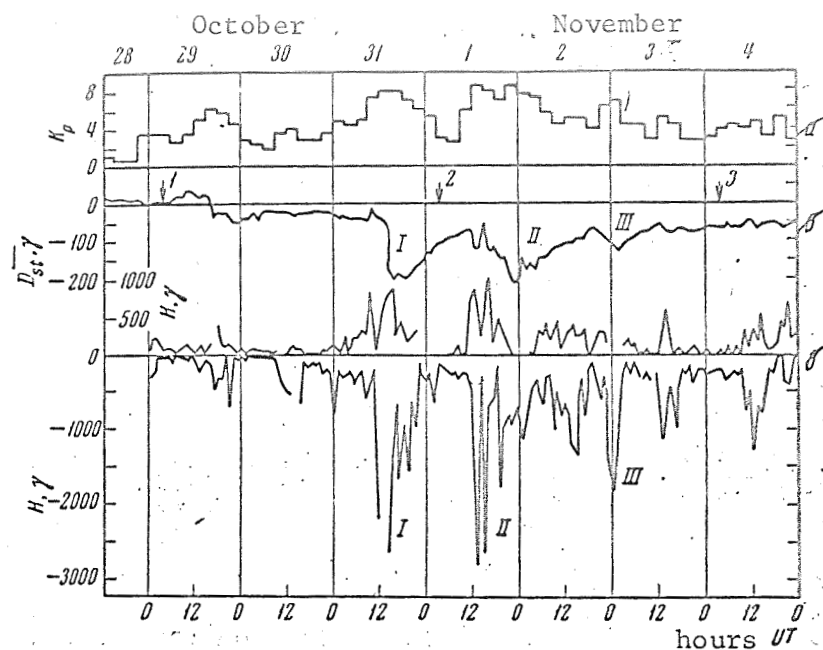


Figure 1. Geomagnetic situation in the period October 29 - November 4, 1968: a -  $K_p$ -Index; b -  $D_{st}$ -Variation, computed from 5 stations spaced by longitude; c - Maximal, at a given hour, deviations of the H-component from the quiet level, computed from 14 high-latitude stations. The arrows 1-3 denote the moments the satellite passed through one and the same regions of the radiation belts, for which data were available.

were carried out at low altitudes, and the results cannot be interpreted unequivocally: the increase in intensity could have been the result either of injection, or of a redistribution of particles by pitch-angles. The measurements described in [3-5], first made near the equatorial plane, and the observed effects were clearly caused by injection. These phenomena are closely connected with the increased intensity of polar disturbances and probably are of great interest for understanding the dynamics of the magnetosphere as a whole.

There was an analogous effect during the storm of October 29 - November 4, 1968. Below we analyze the data obtained on the satellite "Molniya-1" during this storm.

2. Figure 1 illustrates the geomagnetic conditions in the investigated period of October 29 - November 4, 1968: a)  $K_p$ -index; b)  $D_{st}$ -variation, computed from five stations spaced according to longitude (M. Bour, San Juan, Honolulu, Kakioka, Tashkent); c) maximal deviations at a given time of the H-component from the quiet level, computed from 14 high-latitude stations, uniformly distributed both by longitude and by latitude. In practice these are the  $A_{fl}$ - and  $A_u$ - indices [6], i.e., the characteristic values of the high-latitude electric streams  $A_l$  — west ( $-\Delta H$ ) and  $A_u$  — east ( $+\Delta H$ ). /2272

The analyzed storm was very complex: On October 26 at 18 hours 32 minutes a sudden beginning was observed. However, substantial changes in the field took place only on October 29, and consisted of at least three disturbances overlapping one another. During two of the strongest of them (I, II)  $D_{st}$  — the variation reached  $\sim 200 \gamma$ ; during III —  $150 \gamma$ . In all three cases of disturbances at high latitudes a significant increase was observed in the western electro-stream: amplitude of negative bays reached  $> 2600 \gamma$  (I),  $\sim 2800 \gamma$  (II) and  $\sim 1800 \gamma$  (III). Relative to the eastern electro-stream, we can say that it varied in parallel with the western, but had an amplitude several times smaller.

3. Figure 2 gives the counting rates of the  $HC_1$  channel averaged for one minute ( $E_e > 250$  keV) as a function of the parameter L (the MacIlvine parameter) for several flights in the radiation belts. The region of the gap between the belts ( $L \sim 3$ ) was intersected by the satellite at  $\sim 0400$  hours UT near the equatorial plane.

Curve 1 gives the profile of the belt under quiet conditions (flight before the storm on October 29). The space between the inner and outer belts is clearly seen for  $L \sim 3$ . Curve 2 gives the flight on November 1, immediately after the first series of intense substorms. It is clear that the electrons were injected deeply into the space where their intensity increased by more than two orders of magnitude. Curve 3 gives the profile of the belt on November 4 at the end of the recovery phase of the storm. It is clear that the number of injected electrons had increased, and the inner front of

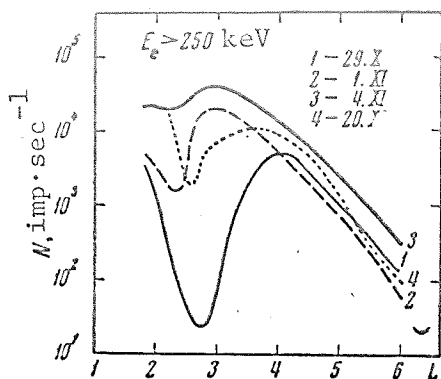


Figure 2. Dependence of counting rate of channel  $HC_1$  ( $E_e > 250$  keV) on  $L$ .

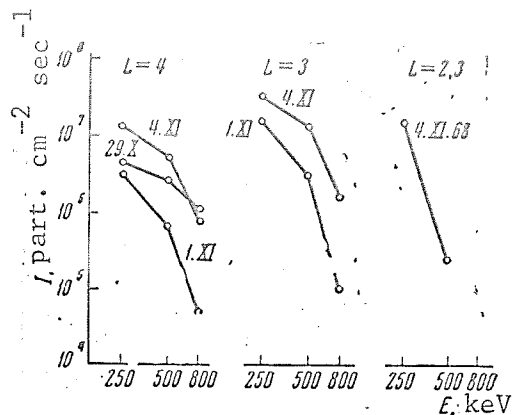


Figure 3. Integral spectra of electrons with energies of  $E_e > 250$ , 500 and 800 keV for  $L = 2.3 - 4$ .

the belt had advanced nearer to Earth. Curve 4 (flight of November 20, i.e., after approximately two weeks following end of the storm) illustrates the disappearance of the injected electrons in the region of the gap.

Readings from the channels with higher thresholds ( $E_e > 500, 800$  keV) also indicate the injection of particles of these energies; however, they do not penetrate so deeply: the spectrum in the region  $L < 3$  becomes significantly softer.

Figure 3 shows the integral spectra of electrons with energies of  $E_e > 250, 500$  and  $800$  keV in the investigated period (October 29, November 1, November 4). For  $L < 3.5$  in the absence of injection into the gap, we can never reliably distinguish the electrons on the background of protons; therefore, the spectra for October 29 for  $L < 3.5$  are not shown. For  $L \sim 2.3$  /2273 even on November 1 in the presence of an additional contribution from injected electrons into the reading of the HC detector, only the reading of the channel with  $E_e > 250$  keV exceeded the background level, produced by the protons. Only after an additional injection did the reading of the  $HC_2$  channel ( $E_e > 500$  keV) substantially exceed the level of the protons.

From comparison of the spectra for  $L = 3$  and  $L = 2.3$ , on November 4, it was obvious how strongly the spectrum was softened for  $L = 2.3$ . When the spectrum was approximated by a power law (between points 250 and 500 keV) for  $L = 3$  the exponent of the spectrum was  $n \approx 2$ ; for  $L = 2.3$   $n \approx 6$ . With an approximation of the exponent between these same points, for  $L = 3$  the constant  $E_0 = 270$  keV; for  $L = 2.3$ ,  $E_0 = 60$  keV.

This result agrees with the data from reference [5], in which it was shown that, with a strong injection of electrons with energies of 290 - 690 keV into the inner belt, no variations are observed in the electrons with energies of 690 - 1700 keV.

4. The onset of large electron fluxes with energies in the hundreds of keV for  $L = 2 - 3$  during strong storms means either an acceleration directly in these clouds or a rapid transport from more distant clouds accompanied by adiabatic acceleration.

A possible explanation of the injection may be the effect given by Alfven [7] — the drift of particles in the field of the magnetic dipole and the electric field. Under the action of magnetic drift, the particle passes a certain potential difference into the electric field and either increases or decreases its energy. Those particles which are accelerated approach the Earth. Evaluations from Alfven's formulas ([7], Section 2.6.1) show that for injection of electrons having energies of  $E_e > 250$  keV for  $L$  up to  $\sim 2.5$  there must be potential differences, between  $L \sim 5$  and the Earth, of  $\sim 200$  kV.

The greatest potential difference is reached along the loops which separate the closed and the unclosed orbits where the ratio of initial ( $L_i$ ) and final ( $L_f$ ) values of the cloud parameters comprises  $\sim 1.8$ . Here the energy (in the nonrelativistic case) because of conservation of the magnetic moment increases by  $(1.8)^3 \sim 6$  times. On the other hand, the increase in energy is  $\Delta E = e\Delta U$ , where  $\Delta U = \mathcal{E}a(L_i + L_f)$  — is the potential difference on the loop ( $a$  is the radius of the Earth,  $\mathcal{E}$  — is the electric field strength). After denoting by  $E_i$  and  $E_f = E_i + \Delta E = 6E_i$  the initial and final energy, we

obtain:

$$\mathcal{E} = \frac{\Delta E}{ea(L_i + L_f)} = \frac{5}{6} \cdot \frac{E_f}{2,8eaL_f}.$$

When  $E_f = 250$  and  $L_f = 2,5$ , we find the given estimation of the potential.

In order that the effect be irreversible and the particles remain on the new drift clouds, the life time of the electric field must be on the order of a half period of the particle drift along the perturbed trajectory (for electrons with an energy of  $\sim 250$  keV, which are accelerated from  $\sim 40$  keV, the time is  $\sim 1$  hour). At a high drift velocity, the effect of the field is exerted adiabatically, and after the disappearance of the potential difference the particles return to the original orbits. It is possible, mainly for this reason, that no rapid injection of high-energy electrons into the inner belt is observed.

According to existing concepts [8, 9] the large-scale electric fields in the magnetosphere are connected with the polar disturbances (DP). Computation [9] shows that the potential difference  $\Delta U$  between the Earth and the clouds with  $L = 4 - 5$  in the equatorial plane is approximately equal to the potential difference across the polar electro-stream in the ionosphere. Theoretical computation gives for a moderate bay (with perturbation of the magnetic field under a stream of  $\sim 500 \gamma$ )  $\Delta U$  on the order of several tens of kV. On the basis of the experimental data on the velocity of barium clouds an analogous computation is obtained [10]. For more intense bays the theory [9] is applicable only qualitatively; however, the values of  $\Delta U \approx 100 - 200$  kV are fully reasonable.

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If we have a series of bays, then the total effect of their electric fields on the particles has a diffusion character. If the period of the particle drift around the Earth is not too small in comparison with the duration of the bay, the rate of such diffusion for small  $L$  may substantially exceed the diffusion rate under the action of the sudden pulses [11].



In the framework of this interpretation, we can assume that the injection observed by us on November 1, 1968, at 0400 hours UT, took place as a result of the first of intense ( $\sim 2500 \gamma$ ) bay-like perturbations (I) (Figure 1,c). This series began and ended on October 31, after which up to  $\sim 1200$  hours UT on November 1 the field was relatively quiet. Then a second large perturbation (II) took place, and following it in the entire recovery phase of the storm a series of weaker perturbations took place with amplitudes of  $\gtrsim 1500 \gamma$ . Because of the absence of detailed data, we could not observe the dynamics of the injection for the period from November 1 to November 4. The data for November 4 (see curve 3, Figure 2) indicate that in this period an additional injection took place: the front of the injected electrons in comparison with November 1 penetrated deeply; the space between the belts for energies  $E_e > 250$  keV practically disappeared. However, available data do not lead to any conclusion as to whether the advance of the front is the result of some single strong perturbation (for example, II and III) or is the total effect of all the perturbations, taking place between the second and third flights of the satellite (see Figure 1) and producing a rapid, deeply penetrating diffusion.

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